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# DEVELOPMENT OF A DESIGN MANUAL FOR CONCRETE FLOOR SLABS ON GRADE

Army Construction Engineering Research Laboratory

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This study prepared a design manual for concrete slabs on grade subjected to moderate to heavy loads. Existing design procedures were reviewed, theoretical studies were made, and an interim manual was prepared. Information in existing manuals was critically reviewed and applicable material used extensively in the preparation. Assumptions made in the manuals with regard to type and volume of vehicular traffic were re-examined on the basis of a field survey and revised when necessary.

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# FOREWORD

The work described herein was started by the Construction Engineering Laboratory (CEL)* of the Ohio River Division Laboratories for the Office of the Chief of Engineers, in accordance with "Performance and Requirements for PCC Floor Slabs on Grade." It was funded under O&MA Project, "Investigation for Development of Engineering Criteria." The work was completed by the Construction Engineering Research Laboratory. The technical coordinator was Mr. A. Muller.

Acknowledgement is made to the federal agencies and private companies involved in the field survey phase of the work for their helpful cooperation.

Dr. L. R. Shaffer is Director of CERL.

*In October 1968 CEL became the U.S. Army Construction Engineering Research Laboratory (CERL), located in Champaign, Illinois since July 1969.

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## DEVELOPMENT OF A DESIGN MANUAL FOR CONCRETE FLOOR SLABS ON GRADE

### 1 INTRODUCTION

**Background.** In late Fiscal Year 1965, a project was initiated by the Office of the Chief of Engineers to develop a design manual for floor slabs on grade subjected to heavy loads. Current practice is to use manuals developed for buildings and pavements. This is not satisfactory since the loadings, function and environment associated with lightly and heavily loaded floor slabs on grade differ considerably from those of floor slabs in buildings and pavements. Problems such as slab warping, joint failure, and moisture accumulation have reportedly resulted in floor slab failures and unduly high maintenance costs. While other floor slabs have performed satisfactorily, the economy of the designs is unknown. Thus the study was initiated to review the special requirements and problems associated with industrial floor slabs-on-grade subjected to heavy cyclic loadings, and to develop a design manual specifically applicable to such floor slabs. It should be noted that the scope of the manual does not include the design of floor slabs for residential and office buildings, since these are adequately covered in TM 5-809-2.[1]

To achieve the objectives outlined in the preceding paragraph, a literature search was first initiated covering existing design procedures, types and axle loads of vehicles likely to use the floor slabs of such structures, and a review of theoretical approaches available. An interim design manual was prepared and submitted to the Office of the Chief of Engineers for review. This interim design manual was based on information collected during the literature search. Concurrently a field survey of selected warehouse sites was initiated to review and, if necesary, modify the design criteria established on the basis of the literature search. A revised design manual TM 5-809-12,[2] superseding the interim design manual and incorporating the field survey data and the interim approach, has been prepared.

**Purpose and Scope.** The purpose of this report is to describe briefly the procedures used to develop the proposed design manual. The assumptions made and the design procedures recommended are discussed. One chapter summarizes the results of the field survey which, as explained earlier, led to the modification of the interim design manual. It should be noted that existing design manuals TM 5-822-6,[3] TM 5-818-1,[4] and TM 5-818-2,[5] after being subjected to critical reviews relative to slabs for heavy loads, have been utilized extensively in the development of the new criteria for concrete floor slabs on grade.

### 2 BASIS FOR FLOOR SLAB DESIGN

**Design Variables.** The thickness necessary to provide the desired load-carrying capacity of a rigid floor slab is a function of five principal variables:

a. loads resulting from moving live loads and stationary live loads,
b. configuration of the vehicle wheels or tracks,
c. volume of traffic during the design life of the pavement,
d. modulus of rupture (flexural strength) of the concrete,
e. modulus of subgrade reaction.

**Moving Live Loads.** All classes of vehicles which might be expected to use industrial floor slabs are divided into three general groups:

a. forklift trucks,
b. other pneumatic and solid-tired vehicles,
c. track laying vehicles.

Data on groups (b) and (c) have been compiled for TM 5-822-6. To obtain a complete set of data, it was considered necessary to collect information on forklift trucks only. It is to be noted that the majority of vehicular traffic using industrial floor slabs would

[1] *Concrete Structure Design for Buildings*, TM 5-809-2/AFM 88-3, Chap. 2 (Department of the Army and the Air Force, January 1967).

[2] *Concrete Floor Slabs-on-Grade Subjected to Heavy Loads*, TM 5-809-12 (Department of the Army and the Air Force, Draft).

[3] *Rigid Pavements for Roads, Streets, Walks, and Open Storage Areas*, TM 5-822-6/AFM 88-7, Chap. 1 (Department of the Army and the Air Force, 1969).

[4] *Procedures for Foundation Design of Buildings and Other Structures (Except Hydraulic Structures)*, TM 5-818-1/AFM 88-3, Chap. 7 (Department of the Army, 1961).

[5] *Pavement Design for Frost Conditions*, TM 5-818-2 (Department of the Army, 1965).

**Table 1**

**Design Data**

| Category | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| Capacity (lbs) | 4000 | 6000 | 10000 | 16000 | 20000 | 52000 |
| Design Axle Load (lbs) | 10000 | 15000 | 25000 | 36000 | 43000 | 120000 |
| No. of Tires | 4 | 4 | 6 | 6 | 6 | 6 |
| Type of Tire | Solid | Solid | Pneumatic | Pneumatic | Pneumatic | Pneumatic |
| Tire Contact Area (sq. in.) | 27.0 | 36.1 | 62.5 | 100 | 119 | 316 |
| Effective Contact pressure (psi) | 185 | 208 | 100 | 90 | 90 | 95 |
| Tire Width (in.) | 6 | 7 | 8 | 9 | 9 | 16 |
| Wheel Spacing (in.) | 31 | 33 | 11-52-11 | 13-58-13 | 13-58-13 | 20-79-20 |
| Aisle Width (in.) | 90 | 90 | 132 | 144 | 144 | 192 |
| Spacing Between Dual Wheel Tires (in.) | — | — | 3 | 4 | 4 | 4 |

undoubtedly be forklift trucks. In 1973 several manufacturers were asked to supply information on six forklift truck categories established in a previous survey of industry and government specifications. The pertinent design data for these categories are shown in Table 1.

**Traffic Volume.** An estimate of the traffic volume likely to use the floor slab is a necessary design input variable. Traffic volume is characterized by the fatigue effects which must be accommodated by the slab during the design life. Traffic volumes used to develop the design manual are discussed in detail in Chapter 3.

**Subgrade.** Most of the information contained in the section of the manual on subgrade was obtained from existing design manuals after they were critically reviewed for applicability. Table 2 indicates a range of values of the modulus of subgrade reaction (k) as a function of material type. Since slab design thickness is not highly sensitive to the modulus of subgrade reaction, the use of costly plate-bearing tests is unusually unnecessary. Tabular average values are applicable for all soils except those having special characteristics such as decrease of strength on working and rolling and expansion when allowed to absorb moisture.

Provision is made in the design manual for nonuniform subgrade support of rigid floor slabs. This condition may be encountered when a floor slab is constructed in an area of highly variable soil types or soil conditions. A nonuniform subgrade may also result when a floor slab is located partially on a cut area and partially on a fill area. An illustrative sketch is shown in Figure 1. Where nonuniform subgrade materials are encountered, steel reinforcement is recommended to control slab cracking. Nonuniform subgrade support can result in slab cracking due to stress concentrations induced by an abrupt change in the supporting capacity of the subgrade. These stress concentrations are encountered when some portion of the slab is forced to move with a yielding subgrade while the remaining portion is restrained from moving by a relatively less-yielding subgrade. The slab is thus forced to bridge the discontinuity and, in so doing, experiences rather high stresses. In order to provide quantitative estimates of these induced stresses, the effects of nonuniform subgrade support have been evaluated analytically. A finite element analysis[6] was performed on a slab loaded to the maximum static allowable load, supported in one portion by a material of one subgrade strength and in the other portion by a material of different subgrade strength. Utilizing the "working stress method," reinforcing steel percentages were computed for varying slab thicknesses and degrees of nonuniform subgrade support. The "working stress method" was considered appropriate since all other considerations in the floor slab design process (moving live loads, stationary live loads) are based on working stress concepts. Use of maximum allowable static loads tended to collapse the data along a single line. A single curve showing the recommended reinforcing steel percentage versus the variation in subgrade strength has been prepared and is included

[6]C. F. Stelzer and W. R. Hudson, "A Direct Computer Solution for Plates and Pavement Slabs," *Research Report 56-9* (Center for Highway Research, University of Texas, October 1967).

**Table 2**

**Typical Values of Modulus of Subgrade Reaction**

| Type of Materials | 1 to 4% | 5 to 8% | 9 to 12% | 13 to 16% | 17 to 20% | 21 to 24% | 25 to 28% | Over 29% |
|---|---|---|---|---|---|---|---|---|
| | **Modulus of Subgrade Reaction, k, in lb/cu. in. for Moisture Contents of** | | | | | | | |
| Silts and Clays Liquid Limit 50 (OH, CH, MH) | — | 175 | 150 | 125 | 100 | 75 | 50 | 25 |
| Silts and Clays Liquid Limit 50 (OL, CL, ML) | — | 200 | 175 | 150 | 125 | 100 | 75 | 50 |
| Silty and Clayey Sands (SM & SC) | 300 | 250 | 225 | 200 | 150 | — | — | — |
| Gravelly Sands (SW & SP) | 300+ | 300 | 250 | — | — | — | — | — |
| Silty and Clayey Gravels (GM & GC) | 300+ | 300+ | 300 | 250 | — | — | — | — |
| Gravel and Sandy Gravels (GW & GP) | 300+ | 300+ | — | — | — | — | — | — |

NOTE: "k" values shown are typical for materials having dry densities equal to 90 to 95% of the maximum CE 55 density. For materials having dry densities less than 90% of maximum CE 55 density, values should be reduced by 50 lb/cu in., except that a "k" of 25 lb/cu in. will be minimum used for design.

Values shown may be increased slightly if density is greater than 95% maximum CE 55 density, except that a maximum "k" of 300 lb/cu in. will be used for design.

in the design manual. This curve is shown here in Figure 2.

## 3 SLAB DESIGN METHOD

**Design Requirements.** Definitive life-cycle cost data were available to dictate a design life for the floor slabs. Examination of amortization costs for structures revealed a nearly constant rate after 40 to 50 years, which provided a basis for selection of a 50-year design life. Critical stresses are based on Westergaard analysis for loading at a free edge, except that free-edge stresses are reduced by 25% to account for load transfer across joints. This is considered reasonable since, in a typical warehouse operation, only rarely will the full design load act on a free edge. An exception would be doorways carrying vehicular traffic, for which special provisions are provided in the manual. An impact factor of 1.25, as currently used in the Corps of Engineers design procedure for roads and streets,[7] was included for all vehicles. The impact factor is used to provide for the effects of rapid vehicle braking or possible vehicle bouncing which could occur when the vehicle departs an inclined ramp to a level floor. Stresses were further modified by incorporating appropriate design factors for the effects of load repetition (fatigue).

**Design Assumptions.** The following assumptions have been made with regard to applied loading:

a. The prime loads on the floor slabs will be forklift trucks of various categories as described previously.
b. Vehicles other than forklift trucks can be substituted as equivalent applications of forklift

[7] *Rigid Pavements for Roads, Streets, Walks, and Open Storage Areas,* TM 5-822-6/AFM 88-7, Chap. 1 (Department of the Army and the Air Force, 1969).

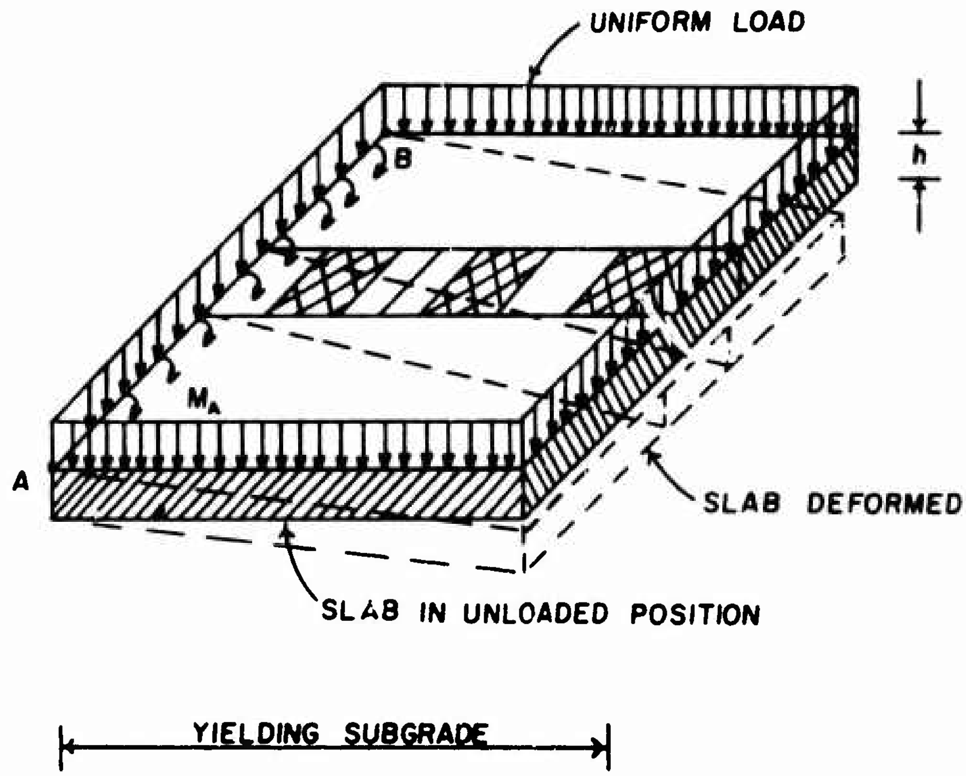


**Figure 1.** Nonuniform subgrade support.

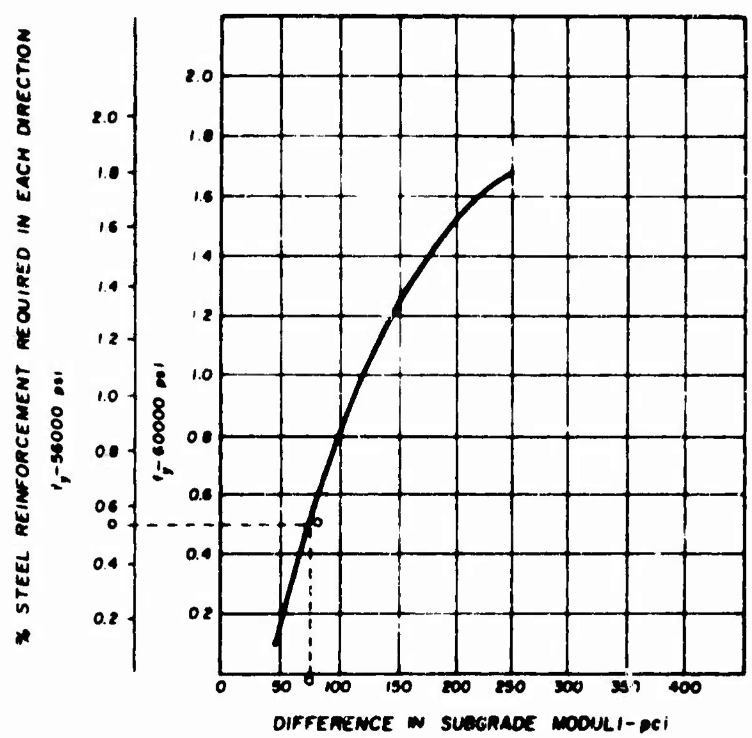


**Figure 2.** Recommended steel reinforcement for areas of nonuniform subgrade support.

trucks. The specific equivalency relationships were taken from TM 5-822-6.

The following assumptions have been made with regard to the physical properties of the slab-subgrade system and its behavior upon application of loads:

a. Modulus of elasticity, E, and Poisson's ratio, $\mu$, for the concrete are $4.0 \times 10^6$ psi and 0.20, respectively.
b. Pavement thickness is uniform.
c. The subgrade provides uniform support to the floor slab for each major portion of the slab supported on a single strength subgrade.
d. The floor slab and the subgrade behave elastically under all loadings.
e. Floor slab stresses of various magnitudes may be equated to an equivalent number of applications of a constant stress under cyclic loading.

**Vehicular Traffic.** The development of a design method to satisfy the design requirements described previously follows the procedures developed for the design of roads and streets.[8] Accordingly, all traffic expected to use floor slabs is compared to a single, basic loading, and after the establishment of equivalent coverage factors, the entire design is converted to various specified coverage levels of that base. The loading selected for the base is a single 25 kip axle load having the wheel configuration of Category III (Table 1). The choice of the basic loading is arbitrary and was selected to provide a reasonable spread in the loadings and traffic volumes likely to be encountered under normal conditions.

Before proceeding with the design method, it was necessary to establish the number of vehicle passes that would produce statistically one coverage on the minimum aisle width specified in Table 1. The method of determining the pass-coverage relationship is based on the method described in a technical report,[9] as follows:

> In this computation the critical portion of the traffic lane was considered to be a line located at points in the traffic lane where repetitions of the load are greatest. It generally passes through the center line of the tire contact area (or midway between contact areas for dual tires) when the vehicle is centered in the traffic lane. A load is applied to the critical line whenever the tire contact area wanders less than a distance X', equal to one-half the width of the tire contact area (or twin areas for dual tires), from its centered position. For dual tires a distance X' is used to designate one-half the spacing between tire contact areas, and loads are not applied to the critical line when the vehicle wanders a distance less than X' from its centered position. Traffic distribution may be represented by the "normal distribution curve" and that 85 to 90 percent of this traffic is applied within the traffic lane. The area under the normal distribution curve corresponding to an abscissa of X (reduced by that corresponding to X' for duals) is the percentage of the total operations which apply a load to the critical line. Thus, the number of operations per coverage is equal to the total number of operations divided by the percentage of operations which apply a load to the critical line. That is, the number of operations per coverage is equal to the reciprocal of the product of the number of axles and the percentage of the area under the probability curve corresponding to an abscissa of X (reduced by that corresponding to X' for duals). In order to read the percentage of operations applying a load to the critical line from tables of probability functions, it is necessary to determine values for X (and X') in terms of standard deviations. To accomplish this, a lane of wander must be defined. This lane is taken as the traffic lane width less the distance between the outside edges of the tire contact areas of a vehicle. It is assumed to be equal to ±1.5 standard deviations (based on assumption that 85 to 90 percent of the traffic is applied within the lateral limits of the traffic lane).

The following symbols represent values, either defined or assumed, determined on the basis of a study of dimensions, wheel configuration, load, tire pressure, and operating characteristics of standard civilian, commercial, and military vehicles expected to use roads and streets at military installations:

a. $P_W$ = width of traffic lane; see Table 1.
b. $T_W$ = average width of tire or track; i.e. sum of widths of tires or tracks for all vehicles within a specified load range divided by number of vehicles within this load range.
c. $W_S$ = average wheel spacing; i.e. sum of center-to-center wheel or track spacings for all vehicles within a specified load range divided by the number of vehicles within this load

[8] P. F. Carlton, *Development of Rigid Pavement Thickness Requirements for Military Roads and Streets*, Technical Report No. 4-18 (U.S. Army Engineer Division, 1961).

[9] *Revised Method of Thickness Design for Flexible Highway Pavements at Military Installations*, Technical Report No. 3-582 (U.S. Army Corps of Engineers, 1961).

range.

d. $S$ = spacing between dual-wheel tires.

e. $C_w$ = width of tire or track contact area; assumed to be equal to 75 percent of $T_w$ for pneumatic tires, and equal to $T_w$ for solid rubber tires.

f. $B_w$ = wander; i.e. width of that portion of traffic lane available for wander of vehicle; assumed to be equal to $\pm 1.5\sigma$.

g. $\sigma$ = standard deviation; assumed to be equal to $\frac{B_w}{3}$.

h. $X$ = one-half the width of the tire contact area for single wheels or one-half the distance between the outside edges of tire contact areas for dual wheels.

i. $X'$ = one-half the distance between the inside edges of tire contact areas for dual wheels.

j. $n$, $n'$ = values of $X$ and $X'$ in terms of $\sigma$; for single wheels and tracks, $n = \frac{C_w}{2\sigma}$; for dual wheels, $n = \frac{1.75\,T_w + S}{2\sigma}$ and $n' = \frac{0.25\,T_w + S}{2\sigma}$.

k. $A_n$, $A_{n'}$ = area under probability curve corresponding to abscissa of $n$ or $n'$.

The following are examples of computations required to determine the number of operations per coverage for representative configurations, taken from Table 1.

a. *Single axle, single wheel.* (Category II)

Known: Single axle

Single wheel

Solid tire

10- to 15-kip load

$T_w = 7.0$ in.

$W_s = 33$ in.

$P_w = 90$ in.

Assumed: $C_w = T_w = 7.0$ in.

$B_w = \pm 1.5\sigma$

Then:

$$B_w = P_w - (W_s + C_w)$$

$$= 90 - (33 + 7.0)$$

$$= 90 - 40.$$

$$= 50 \text{ in.}$$

$$\sigma = \frac{B_w}{3} = \frac{50}{3} = 16.67 \text{ in.}$$

$$n = \frac{C_w}{2\sigma} = \frac{7.0}{2(16.67)} = 0.2100$$

$A_n$ = 16.63 percent (read from tables of probability functions)

Thus, only 16.63 percent of the operations apply a load to the critical portion of the traffic lane. The number of operations per coverage of this single-axle, single-wheel configuration is equal to the reciprocal of the product of the number of axles and the area under the probability curve corresponding to an abscissa of n; therefore,

$$\text{Operations per coverage} = \frac{1}{(1)(A_n)} = \frac{1}{(1)(0.1663)}$$

$$= 6.012$$

In other words, the critical portion of the traffic lane is loaded one time every 6.012 operations (passes) of this configuration.

b. *Single axle, dual wheels.* (Category IV)

Known: Single Axle

Dual wheels

Pneumatic tires

25- to 36-kip load

$T_w = 9$ in.

$W_s = 71$ in.

$S = 4$ in.

$P_w = 144$ in.

Assumed: $C_w = 0.75\ T_w = 6.75$ in.

$B_w = \pm 1.5\sigma$

Then: $B_w = P_w \;\; (W_s + 1.75\, T_w + S)$

$= 144 \;\; (71 + 15.75 + 4)$

$= 144 \;\; 90.75$

$= 53.25$ in.

$\sigma = \dfrac{53.25}{3} = 17.75$ in.

$$n = \frac{1.75\, T_w + S}{2\sigma} = \frac{15.75 + 4}{35.50}$$

$$= \frac{19.75}{35.50}$$

$n = 0.556$

$$n' = \frac{0.25\, T_w + S}{2\sigma} = \frac{2.25 + 4}{35.50}$$

$$= \frac{6.25}{35.50}$$

$n' = 0.176$

$A_n = 42.20$ percent (read from tables of probability functions)

$A_{n'} = 13.98$ percent (read from tables of probability functions)

$A_n \;\; A_{n'} = 28.22$ percent

Thus, 28.22 percent of the operations of each axle apply a load to the critical portion of the traffic lane. The number of operations per coverage of this single-axle, dual-wheel configuration is equal to the reciprocal of the product of the number of axles and the difference in the areas under the probability curve corresponding to abscissas of n and n'; therefore,

$$\text{Operations per coverage} = \frac{1}{(1)\,(A_n \;\; A_{n'})}$$

$$= \frac{1}{(1)\,(0.2822)} = 3.543$$

In other words, the critical portion of the traffic lane is loaded one time every 3.543 operations (passes) of this configuration.

Table 3 indicates the results of the calculations pertinent to floor slab traffic. It should be noted that coverage is not to be construed as one application of the design load to each point of the entire width of the aisleway, but rather as a relatively small portion thereof. This lateral distribution of traffic over a relatively small width of the traffic lane is referred to as "channelization."

**Table 3**

**Pass Coverage Ratios**

| Category | Maximum Axle Load (lb) | Number of Passes to Produce One Coverage |
|---|---|---|
| I | 10,000 | 7.417 |
| II | 15,000 | 6.012 |
| III | 25,000 | 3.824 |
| IV | 36,000 | 3.543 |
| V | 43,000 | 3.543 |
| VI | 120,000 | 2.423 |

**Equivalent Coverage Factors.** The loading equivalencies between the 25,000 lb basic axle loading and the other vehicles is determined through the use of equivalent coverage factors. These are conversion factors expressing the relative severity of one operation of each design vehicle in terms of the respective coverages of the basic loading.

In order to express the relative severity of loading between different vehicles, the comparison must be made on an equal basis for all vehicles. To facilitate this computation, an arbitrary coverage level of 5000 was selected for the comparative computations. The corresponding design factor for load repetition is 1.30.

The slab thickness necessary to support a given loading can be written in the following form:

$$h = \left[\frac{6\, D_f\, P(M/P)}{\sigma}\right]^{1/2} \qquad \text{[Eq 1]}$$

where h = slab thickness (in.)

$D_f$ = Design factor, 1.00 + 0.25 + 0.30 = 1.55

P = Design wheel load (lbs) (.75 × maximum wheel load)

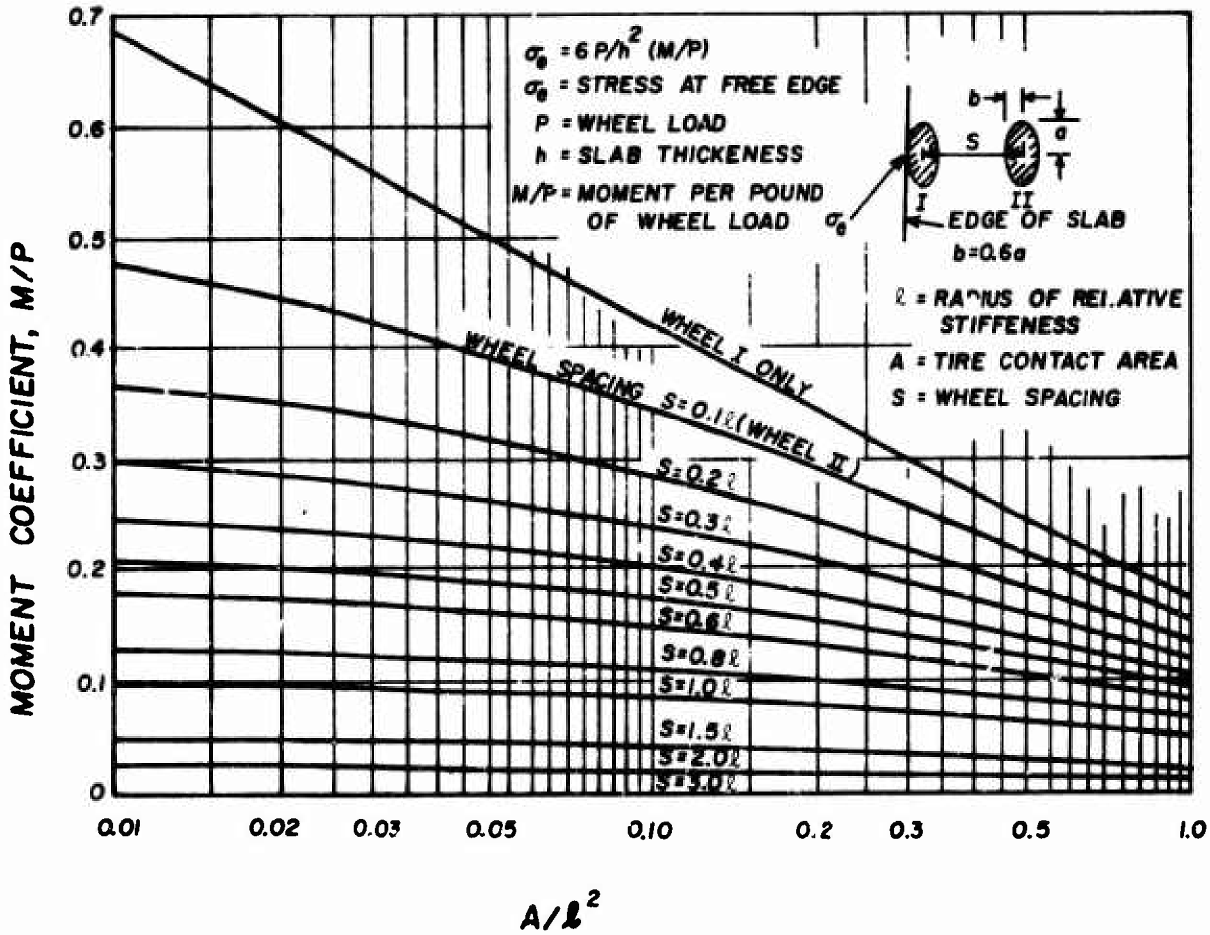


**Figure 3.** M/P vs $A/l^2$ curves for edge loading.

M/P = maximum moment per pound of wheel load induced by all wheels of the axle

$\sigma$ = concrete flexural strength (psi)

h = slab thickness (in.)

$\mu$ = Poisson's ratio for concrete

k = subgrade modulus taken as 100 psi

The design wheel load, P, is 75 percent of the maximum wheel load specified in Table 1. This reduction is a convenient way of incorporating the design assumption that streses at a pavement edge are reduced 25 percent to account for load transfer across joints.

Values of M/P can be determined from charts of $A/l^2$ versus M/P presented in Figure 3. A is the contact area per tire, $l$ is the radius of relative stiffness of the slab given by the following equation:

$$l = \left[\frac{Eh^3}{12(1-\mu^2)k}\right]^{1/4} \quad \text{[Eq 2]}$$

where E = modulus of elasticity of the concrete (psi)

In developing the equivalent coverage factors, the pavement thickness required for 5000 coverages of each loading category is determined on the basis of Equation 1. This thickness is then expressed as a percentage of design thickness required for 5000 coverages of the basic loading. Using the thickness-versus-coverage curve, Figure 4, the design thickness required for each loading category can be converted to equivalent coverages of the basic loading. The equivalent coverages of the basic loading are then divided by the quantity equal to 5000 times the pass-coverage ratio, and thus the equivalent coverage factors are obtained for each loading. Numerical values for the equivalent coverage factors are shown in Table 4, with computed total coverages at various levels of operation for the entire design life of the

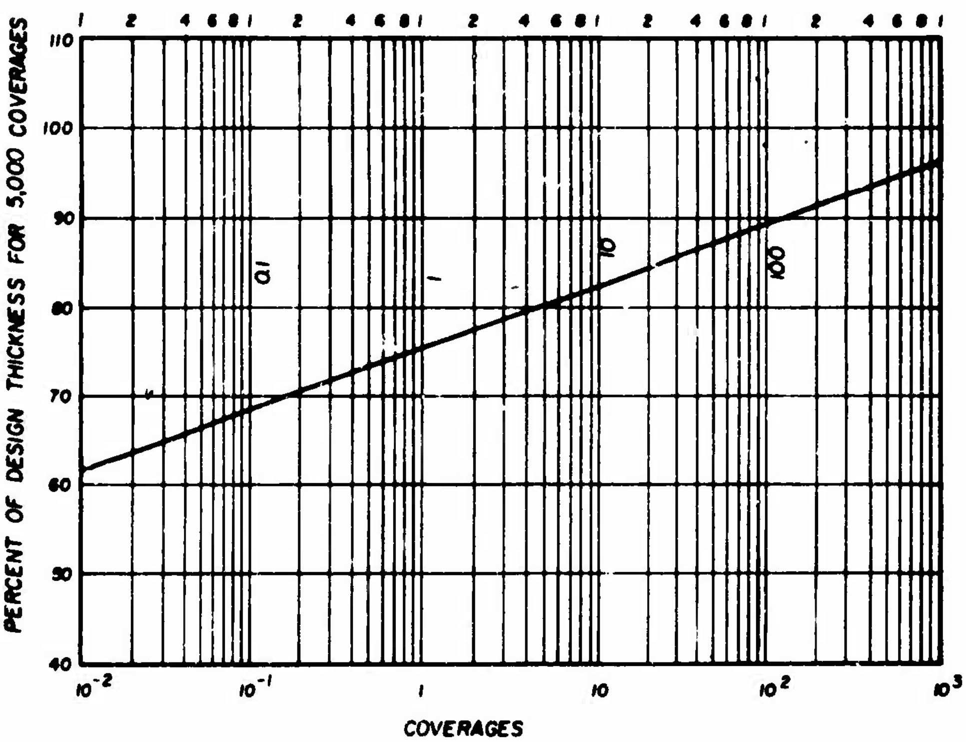


**Figure 4a.** Coverages vs rigid floor slab thickness.

**Table 4**

**Equivalent Coverage Factors (ECF)**

| Category | (1) Required Thickness for 5000 Coverages, in. ($k = 100$ lbs/in$^3$) | (2) % of Basic Loading | (3) Coverages of Basic Loading | (4) $\frac{(3)}{5000}$ | (5) Pass/Coverage Ratio | (6) ECF (4)/(5) |
|---|---|---|---|---|---|---|
| I | 5.84 | 81.1 | 8 | .0016 | 7.417 | $2.16 \times 10^{-4}$ |
| II | 7.22 | 100.3 | 5,400 | 1.08 | 6.012 | 0.180 |
| III (Basic Load) | 7.20 | 100.0 | 5,000 | 1 | 3.824 | 0.262 |
| IV | 8.43 | 117.1 | 440,000 | 88 | 3.543 | 24.8 |
| V | 9.32 | 129.4 | 4,200,000 | 840 | 3.543 | 237 |
| VI | 15.18 | 210.9 | — | *$8.74 \times 10^{8}$ | 2.423 | $3.61 \times 10^{8}$ |

*Define a new temporary basic loading which requires a 12 in. pavement thickness. Using the 12 in. basic pavement thickness, the Category V pavement thickness is 77.67% of the basic thickness and can therefore sustain 2.5 coverages of the temporary basic loading. The Category VI pavement thickness is 126.5% of the basic thickness and can sustain 2,600,000 coverages of the temporary basic loading. Therefore, the Category VI pavement can sustain $1.04 \times 10^{6}$ times as many coverages as the Category V pavement. If a Category V pavement can withstand 840 coverages of the Category III loading, the Category VI pavement can withstand $840 \times 1.04 \times 10^{6}$ coverages or $8.74 \times 10^{8}$ coverages of the Category III loading.

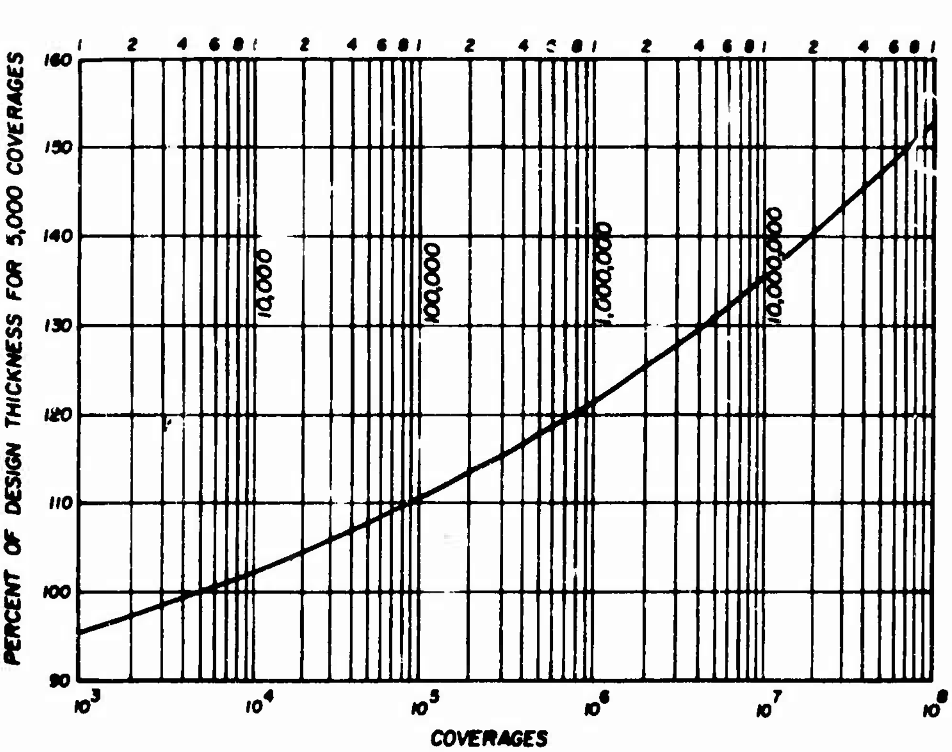


**Figure 4b.** Coverages vs rigid floor slab thickness.

slab. The number of coverages of the basic loading at each level of operation for the design life of the slab is the product of the equivalent coverage factor and the total number of operations. Expressed conversely, the reciprocal of the equivalent coverage factor is the number of actual operations required to equal one coverage of the basic loading.

The slab thickness required for 5000 coverages of the basic loading is determined through a trial-and-error procedure which is completed when the assumed slab thickness is the same as that found from Equation 1. For illustration purposes only, the last two iterations are shown. The basic loading is the 25 kip axle load Category III forklift truck. The loaded area is 62.5 in.$^2$ per tire, k = 100 lbs per in.$^3$ and the wheel spacings are 11-52-11 inches center to center. In the previous cycle through the solution procedure, Equation 1 yielded a value of h approximately equal to 7 in. The radius of relative stiffness, $l$, is 33.03 in. and $A/l^2 = 62.5/1091 = 0.0573$. From Figure 3, the M/P coefficients for the four tires are $0.484 + 0.244 + 0.025 + 0.017 = 0.770$ for $S/l$ values of 0.0, 0.333, 1.91, and 2.24, respectively. The wheel load, which is one fourth the axle load or 6250 lbs, is reduced 25% to 0.75 (6250) = 4687.5 lbs to incorporate the assumption of 25% load transfer across joints. Since load is directly proportional to stress, this adjustment has the same effect as reducing the critical tensile stress at the pavement edge by 25%. Assuming a concrete flexural strength of 650 lb per in.$^2$ in Equation 1, the required pavement thickness for 5000 coverages of the basic loading is:

$$h = \left[\frac{(6)(1.55)(4687.5)(0.770)}{650}\right]^{1/2} = 7.19 \quad \text{[Eq 3]}$$

For the next cycle of iteration, h is assumed to be 7.2 in. The radius of relative stiffness, $l$, is 33.74 in. and $A/l^2 = 62.5/1138 = 0.0549$. From Figure 3, the M/P coefficients for the four tires are 0.485 + 0.245

+ 0.025 + [illegible] 72 for $S/l$ values of 0.0, 0.326, 1.87, and 2.19, respectively. The new calculated value of h is:

$$h = \left[ \frac{(6)(1.55)(4687.5)(0.772)}{650} \right]^{1/2} = 7.20 \text{ in.} \quad \text{[Eq 4]}$$

Since the calculated value of h is the same (with 3-place accuracy) as that assumed at the beginning of the cycle, the iterative process is completed.

As an example of the use of equivalent coverage factors, let it be required that 250 operations per day of a 10 kip axle load forklift truck be converted into equivalent coverages of the basic 25 kip axle load. The loaded area of the 10-kip vehicle is 27 in.$^2$ per tire, the wheel spacing is 31 in. center to center. Again using a k-value of 100 lbs per in.$^3$, the trial-and-error procedure leads to a required slab thickness of 5.84 in. The corresponding radius of relative stiffness is calculated as $l$ = 28.8 in. From Figure 3, for $A/l^2$, $27/28.8^2 = 0.0326$, the M/P factor for the combined effect of both wheels is 0.636. Using the design factor of 1.55 and a flexural strength of 650 lb per in.$^2$ in Equation 1, the required pavement thickness for 5000 coverages of the 25 kip load forklift truck is 5.84 in. This is only 81.1% of the thickness required (7.20 in.) for a similar number of basic loading coverages. From the stress repetitions curve (Figure 4) 81.1% of the 5000 coverage thickness would sustain the basic 25 kip loading only for eight coverages. Dividing by 5000, it can be seen that one coverage of the 25 kip load is equivalent to 0.0016 coverages of the basic loading. Since the Category I vehicle has a pass-to-coverage ratio of 7.417, the Equivalent Coverage Factor (ECF) is $0.0016/7.417 = 2.16 \times 10^{-4}$ which means that one pass or operation of the 10 kip axle load is equivalent to $2.16 \times 10^{-4}$ coverages of the basic loading. Thus, 250 operations per day or $3.788 \times 10^6$ operations per 50 years is equivalent to $2.16 \times 10^{-4} \times 3.788 \times 10^6 = 818$ coverages of the basic loading during the 50-year design life of the structure.

**Design Traffic.** Due to the wide variations in vehicle loadings and wheel configurations of the probable floor slab traffic, two different design charts were required to cover the range of anticipated traffic. The majority of forklift traffic will be composed of the smaller trucks (25,000 lbs or less). The anticipated volume of forklift truck traffic in excess of 25,000 lbs is relatively small and these vehicles are treated separately in the design manual.

A design index was established to provide simplicity and uniformity of design for the lighter-weight forklift truck traffic. Traffic volumes are expressed in terms of daily operations of various size forklift trucks as shown in Table 5. The number of daily operations selected for each design index was determined from observations of typical warehouse operations. The traffic volumes selected are considered representative of normal warehouse activities. The design chart for these design indexes is shown as Figure 5.

**Table 5**

**Traffic Categories for Design Index**

| Design Index | | Maximum Operations Per Day |
|---|---|---|
| 1 | 10 kip axle load forklift truck | 50 |
| 2 | 10 kip axle load forklift truck | 250 |
| | 15 kip axle load forklift truck | 10 |
| 3 | 10 kip axle load forklift truck | 250 |
| | 15 kip axle load forklift truck | 100 |
| 4 | 15 kip axle load forklift truck | 250 |
| | 25 kip axle load forklift truck | 5 |

Floor slab thickness requirements for Categories IV and V forklift trucks are also shown in Figure 5. The Category VI forklift trucks are shown on a separate design chart (Figure 6) because of significantly higher thickness requirements. All thickness requirements for Categories IV, V, and VI forklift trucks are based on an assumed traffic volume of five operations per day. With these trucks the use of a design index was not considered necessary since the traffic volume is constant. The appropriate design curves were merely designated as to forklift weight.

After establishing the design index, the type and volume of traffic in each category is converted to equivalent coverages of the basic 25 kip axle load. The results of these computations are shown in Table 6.

Thickness requirements for Categories IV, V, and VI were determined directly. Since mixed traffic was not involved, there was no need to convert to coverages of the basic loading. Table 7 indicates the required calculations. Table 7 and Table 8 have been

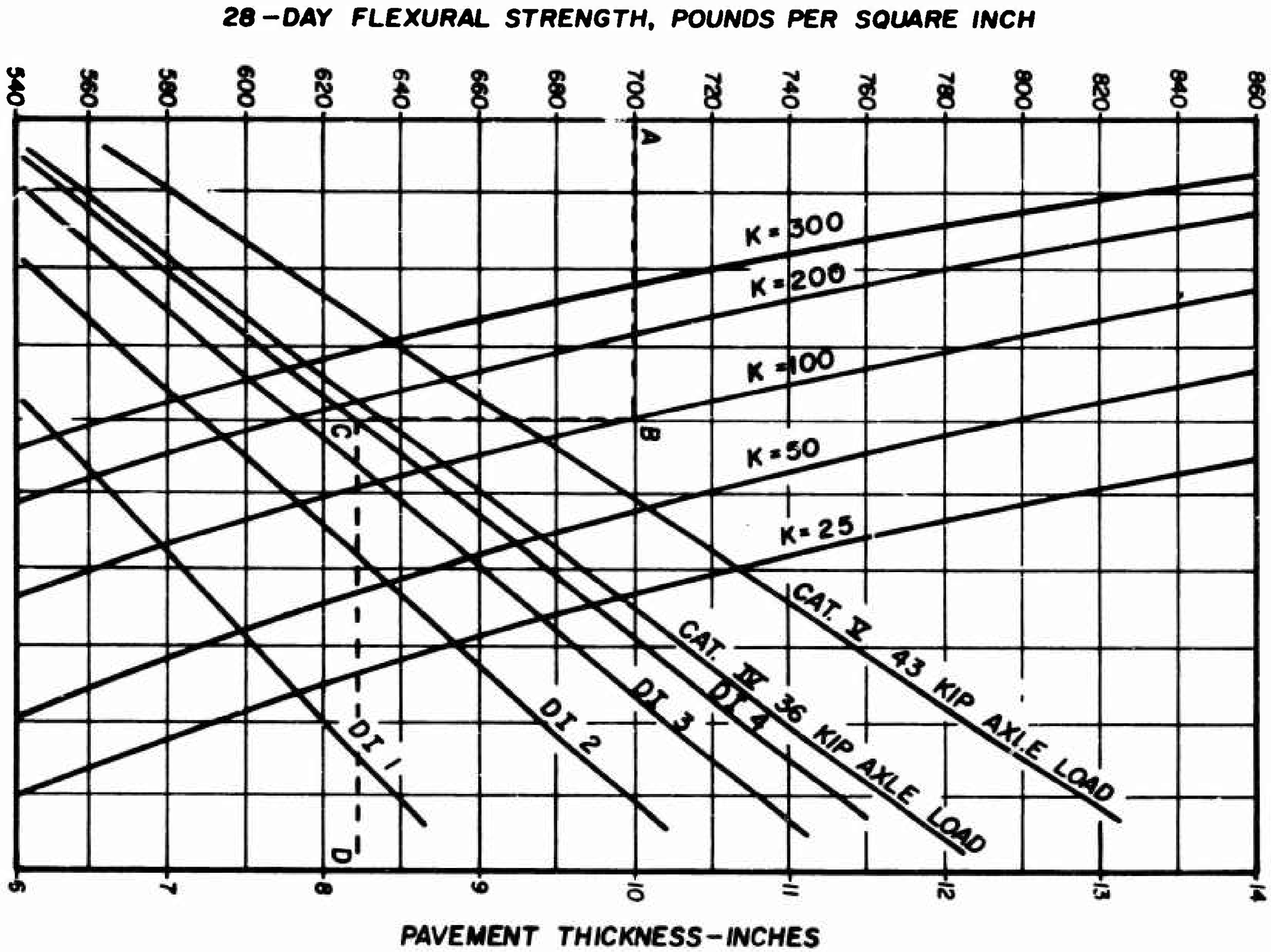


Figure 5. Design curves for concrete slabs: warehouse floor and open storage areas.

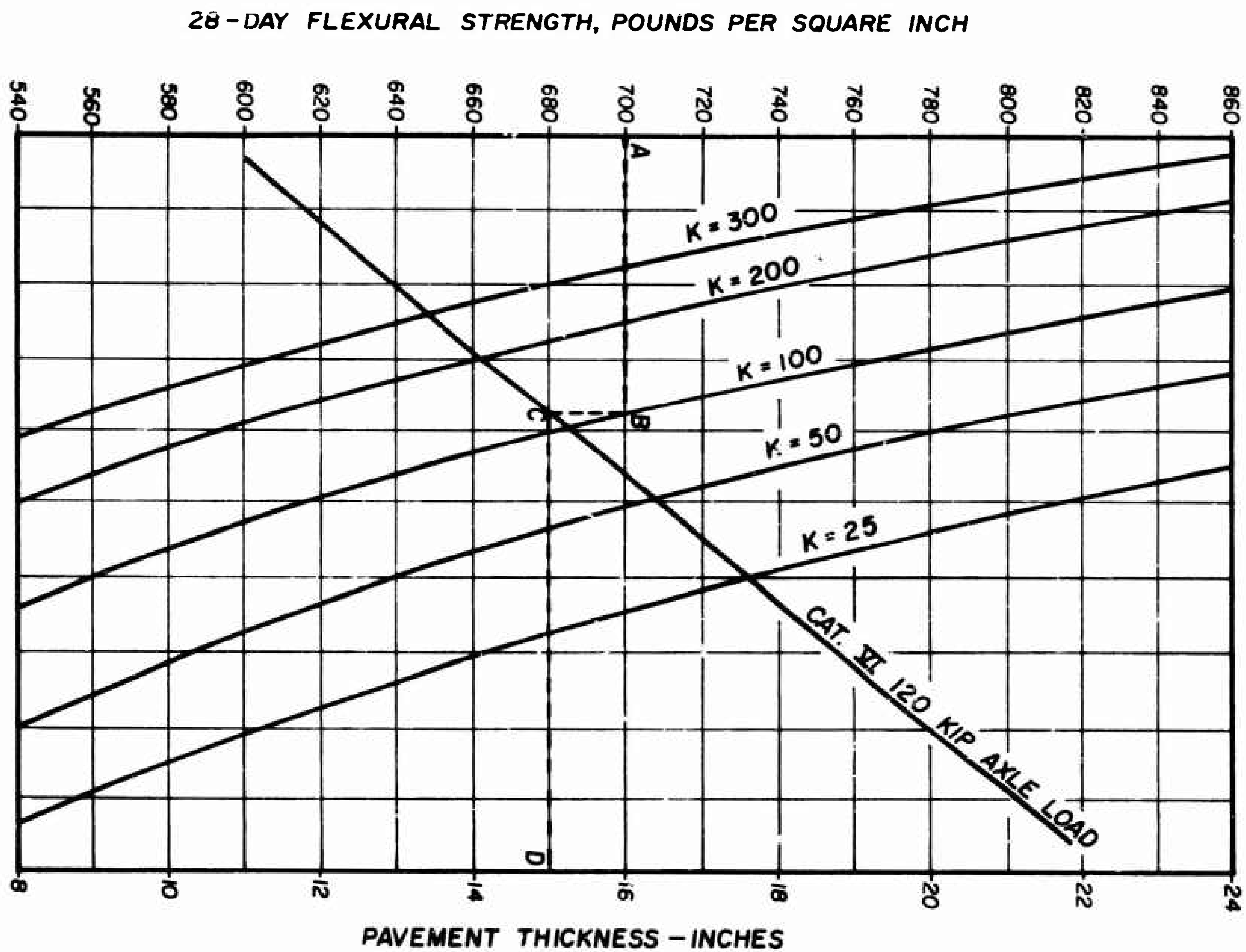


**Figure 6.** Design curves for concrete slabs: warehouse floors and open storage areas (Category VI loading).

**Table 6**

**Design Index in Terms of Equivalent Coverages of Basic Loading**

| Design Index | Operations Per Day Per Category | Operations in 50 Yrs (15,150 Days) | ECF | Coverages of Basic Loading | Total Coverages | Percent Thickness for 5000 Coverages of Basic Loading |
|---|---|---|---|---|---|---|
| 1 | 50 - I | $7.575 \times 10^{5}$ | $2.16 \times 10^{-4}$ | 163.6 | 163.6 | 90.15 |
| 2 | 250 - I | $3.788 \times 10^{6}$ | $2.16 \times 10^{-4}$ | 820 | | |
| | 10 - II | $1.515 \times 10^{5}$ | 0.180 | 27,270 | 28,090 | 105.6 |
| 3 | 250 - I | $3.788 \times 10^{6}$ | $2.16 \times 10^{-4}$ | 800 | | |
| | 100 - II | $1.515 \times 10^{6}$ | 0.180 | 272,700 | 273,500 | 114.9 |
| 4 | 250 - II | $3.788 \times 10^{6}$ | 0.180 | 681,750 | | |
| | 5 - III | $7.575 \times 10^{4}$ | 0.262 | 19,850 | 701,600 | 119.5 |

**Table 7**

**Design Curve Data for Categories IV, V, VI**

| Category | Operations Per Day | Operations in 50 Yrs | Pass/ Coverage Ratio | Total Coverages | Percent of Thickness for 5000 Coverages |
|---|---|---|---|---|---|
| IV | 5 | $7.575 \times 10^{4}$ | 3.543 | 21,380 | 104.7 |
| V | 5 | $7.575 \times 10^{4}$ | 3.543 | 21,380 | 104.7 |
| VI | 5 | $7.575 \times 10^{4}$ | 2.423 | 31,260 | 106.0 |

used to prepare Figures 5 and 6, which present the relationships between concrete flexural strength, subgrade modulus, traffic index or load category, and concrete slab thickness. The required slab thickness is indicated by the right side vertical scale.

The inclusion of other pneumatic and cushion-tired vehicles such as conventional trucks can be evaluated by considering each axle as one forklift truck axle of appropriate weight.

Tracked vehicles, though of considerable gross weight, do not represent a severe floor slab loading since the weight is distributed over a large area. Tracked vehicles are substituted for forklift trucks on a one-for-one basis (Table 8).

**Table 8**

**Load Categories for Tracked Vehicles**

| Tracked Vehicles Maximum Gross Weight (kips) | Forklift Truck Category |
|---|---|
| less than 40 | I |
| 40 to 60 | II |
| 60 to 90 | III |
| 90 to 120 | IV |

Floor slab design requirements for special purpose ordnance, engineer, or transport vehicles producing loadings significantly different than the loadings described herein should be requested from the Office of the Chief of Engineers (ATTN: DAEN-MCE-D).

**Static Loads.** Design criteria for maximum allowable static loads are based on a procedure described by Rice.[10] Negative moments in aisleways between loaded storage bays will be critical for most designs. For each slab thickness, a critical aisle width has been established at which negative moments will attain a maximum value. The maximum negative moments are expressed in terms of the stationary live load intensity. The moments are converted to stresses and thus an allowable stationary live load intensity can be derived from allowable stresses. The resulting allowable maximum, uniformly distributed live loads are indicated in the appropriate section of the manual. Based on the field survey information, under ordinary warehouse operations, stationary live loads will be less than the allowable load; consequently stationary live loads will seldom control the design.

**Reinforced Floor Slabs.** The design criteria incorporated in the manual for reinforced concrete slabs

[10] P. F. Rice, "Design of Concrete Floors on Ground for Warehouse Loadings," *Journal of the American Concrete Institute*, Vol. 29, No. 2 (1957).

**Table 9**

**Field Survey Sites**

| Site | Location | Material Stored | Year Const |
|---|---|---|---|
| H. S. Pogue | Fairfax, Ohio | Dept Store inventory | 1960 |
| American Can Co. | Broadwell, Ohio | Steel wires | 1967 |
| McAlpin Co. (Old) | Cincinnati, Ohio | Textiles, household goods | 1886 |
| McAlpin Co. (New) | Cincinnati, Ohio | Textiles, household goods | 1967 |
| US Army Ars Bldg #92 | Ft. Knox, Kentucky | Tank engines, transmissions | 1959 |
| US Army Ars Bldg #6658 | Ft. Knox, Kentucky | Paints, paper | 1953 |
| US Army Ars Bldg #6564 | Ft. Knox, Kentucky | Office equipment | 1953 |
| US Army Ars Bldg #6570 | Ft. Knox, Kentucky | Ammunition | 1953 |
| GSA Depot | Sharonville, Ohio | Natural Rubber Metallic Chips | 1943 |
| Def Const Supply Cntr | Columbus, Ohio | Heavy machinery | 1942 |
| Def Const Supply Cntr | Columbus, Ohio | Office supplies | 1918 |
| Def Const Supply Cntr | Columbus, Ohio | Very heavy machinery | 1918 |

are based on criteria contained in TM 5-822-6. The basis of the design of reinforced floor slabs is the same as that required for the design of roads, streets, and open storage areas. Therefore, provisions concerning allowable thickness reductions are used without modification.

**Joint Design.** The general description of joint type and usage has been taken from TM 5-822-6. Joint spacing corresponds to that recommended for the design of roads and streets and was subsequently verified by the field inspection of selected warehouse sites. The use of load transfer devices, either in the form of keyed or doweled joints, has been relaxed somewhat with respect to the interim design manual on the basis of the field survey. A special feature of these structures is the use of isolation joints to prevent load transfer and allow for differential settlements between the floor slab and other building components. The recommended design is based on a critical review of design methods by various agencies and a consensus of the personnel involved in the development of the manual.

## 4 FIELD SURVEY

**Data Collection.** A total of 13 warehouses was visited in Cincinnati and vicinity. They included warehouses of various governmental agencies and private industries (Table 9).

A fairly wide range of loadings were observed ranging from household goods such as furniture and appliances to spools of wire for producing staples. The field survey consisted of a team of two engineers who visited the site, observed the condition of the floor slabs and questioned the personnel involved about problem areas. A field questionnaire sheet was prepared for use during the survey (Appendix A). The information requested on the questionnaire is detailed and only rarely were data available in answer to all queries. The questionnaire was completed by the two engineers on site to preserve terminology and adjective descriptions.

**General Observations.** The information collected was not amenable to rigorous analysis. It merely

served as a guide in the development of the technical manual, TM 5-809-12, *Concrete Floor Slabs on Grade Subjected to Heavy Loads.* Some general observations were made which are considered germane to all floor slabs on grade:

*Traffic Volume.* The average daily traffic of forklift trucks will probably seldom exceed 300 trips per day. Generally, traffic volumes are in the range of 100 trips per day for a relatively active warehouse operation.

*Allowable Slab Size.* Floor slabs exhibited shrinkage cracks in nearly every case where the slab exceeded 600 square feet in area. A photograph of a typical shrinkage crack is shown in Figure 7. The particular crack shown in Figure 7 did not interfere with normal operations but is unsightly.

*Isolation Joints.* The need for isolation joints was observed during the field survey. Figure 8 shows some moderately severe distress observed in the vicinity of a column where no isolation joint was provided. The floor slab has cracked severely in this area. An example of a functioning isolation joint is shown in Figure 9. In this instance, the floor slab was not damaged by differential movement occurring between the column and floor slab. Isolation joints are considered essential in all floor slabs to preclude damage due to differential settlement. Figure 10 shows the diamond-shaped isolation joint used in more recent construction.

*Surface Treatment of Floor Slabs.* Approximately half the floor slabs inspected during the field survey had a surface treatment applied to prevent concrete dusting. It consisted of a wax emulsion which produced a shiny, dust-free surface. In one case this treatment caused operational problems because ramps leading to loading docks were too slick for the forklift trucks to climb. In this particular case, the problem was solved by sawing transverse grooves in the ramps to increase traction. However, grooving concrete is a comparatively expensive operation, so an alternate solution which could reduce the cost substantially is offered in the design manual: the use of non-skid abrasive tapes of the type used on stair treads is recommended in areas where traction may be a problem.

*Joint Sealing.* The field survey indicated that about two thirds of the typical floor slab installations were placed without joint sealants. Generally joints were sealed in older floor slabs. The design manual specifies sealed joints shall be optional with the designer.

*Allowable Stationary Live Loads.* Personnel in charge of warehouse operations indicated a definite need for the establishment of allowable stationary live loads. This was particularly true where operations are highly variable such as at the Defense Construction Supply Center in Columbus, Ohio.

The need for thickened edges at doorway openings was also observed in the field study. Cracking due to either free edge loading or subsidence of poorly compacted backfill was noted. Figures 11 and 12 are probably indicative of the latter. Figure 12 is a close-up shot of a crack at a doorway barely visible in Figure 11.

## 5 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the field survey, the following general conclusions are drawn:

a. Traffic volumes, although approximate only, are substantially lower than anticipated. For the 10 kip load category, the average volume was found to be 100 trips per day with an upper limit of about 300 trips per day. Few estimates are available on the percentage of loaded trips, but it appears that 50 to 75% of the above volumes carried full load.

b. With regard to vehicular load, forklift trucks in use did not exceed the 10 kip load at the majority of the sites inspected. Only one site had a 60 kip load forklift truck to transport heavy machinery although these vehicles were utilized to some extent in outside storage areas.

c. The slab size limitation of 600 $ft^2$ set forth in the manual appears to be reasonable to prevent shrinkage cracking. Shrinkage cracks were observed at many sites where this limitation had been exceeded.

d. Cracking of slabs and joint spalling did not seem to interfere with normal warehouse operations as long as adjacent slabs did not settle differentially. In the latter case bouncing of vehicles at the joints created problems in transporting stacked material.

**Figure 7.** Typical shrinkage crack due to large panel.

**Figure 8.** Distress caused by no provision of isolation joint around column pedestal.

**Figure 9.** Functioning isolation joint of older construction, circa 1943.

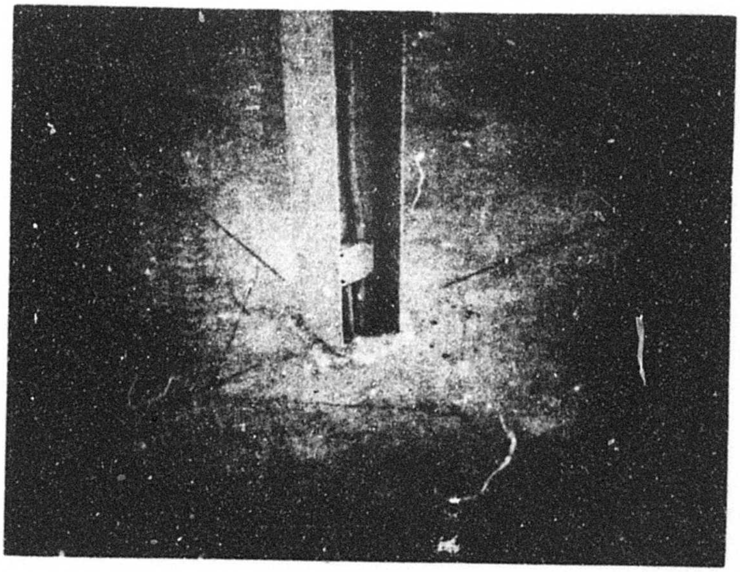

**Figure 10.** Newer construction showing diamond-shaped isolation joint around column.

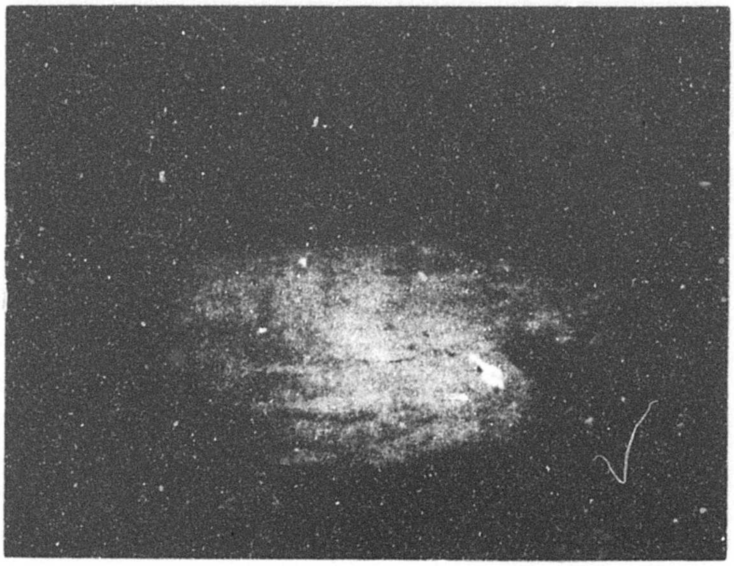

**Figure 11.** Floor slab cracking at doorway (crack barely visible in foreground).

**Figure 12.** Close-up of cracking at doorway. (Crack was moistened prior to photographing to improve contrast.)

e. Contraction and construction joints were usually designed with some load transfer device, either keyed or doweled on recent constructions.

Based on the results of the field survey, the design index chart incorporated in the interim design manual has been revised to de-emphasize heavy volumes and loads. The number of design indexes was reduced from eight to four. The newly prepared design chart is included in the manual as Figure 1. Individual design curves have been prepared for the Categories IV, V, and VI forklift trucks in case they would be required. The curves for Categories IV and V are included in Figure 1. The Category VI design curves are given in Figure 2. A separate paragraph was added stressing the importance of compacting the backfill around columns.

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# APPENDIX A: FIELD SURVEY DATA SHEET

GENERAL

Company: ____________________

Location: ____________________

Type of Storage: ____________________

Year Constructed: ____________________

FLOOR SLABS

Approximate Size: ____________________

Floor Cover: ____________________

Thickness: ____________________

Drainage: ____________________

Base Course: ____________________

Subsurface Information:

____________________

____________________

____________________

Generally above __________ below __________ natural grade.

Remarks:

____________________

____________________

____________________

____________________

____________________

TRAFFIC: Mainly forklift _______, hand cart ________ other specify_______.

Approximate ADT: ____________________________________________

____________________________________________

Maximum gross weight: ________________________________________

Most traffic pneumatic tired _________________ cushion tired ________.

% trips made at full load: ___________________________________

Traffic Lanes and storage bins defined ________ not defined _________.

Aisle width if applicable ____________________________________

PAVEMENT:

Type: ______________________________________________________

____________________________________________

____________________________________________

General Condition: Excellent _______________

Very Good _______________

Good _______________

Fair _______________

Poor _______________

Joints sealed ___________________ unsealed ___________________

keyed ___________________ doweled ___________________

Joint Condition

Reinforced _______________ non-reinforced _______________

Pavement distress ____________________________________________

____________________________________________

____________________________________________

____________________________________________

Remarks ______________________________

______________________________

______________________________

______________________________

______________________________

STATIC LOADS:

What is stored ______________________________

______________________________

Loads are heavy ________ moderate ________ Light ________

Height of stacks ______________________________

Approximate load in psf ______________________________

Storage bin size if applicable ______________________________

Precautions taken for storage of dangerous or potentially dangerous materials ______________________________

______________________________

______________________________

Remarks ______________________________

______________________________

______________________________

______________________________

MISCELLANEOUS:

Type of heating if any: ______________________________

Areas other than storage: ______________________________

Remarks: ______________________________

______________________________

______________________________